

HUDs, HMDs, and SDO: A Problem or a Bad Reputation

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SUMMARY

SDO in modern jet cockpits has been a growing concern. Using a HUD during IMC flight has been thought by many as contributing to SDO. HUD factors affecting SDO include: difficulty in distinguishing upright from inverted flight; clutter; difficulty in assessing rates with digital scales; rapid symbol motion; and use of velocity vector for control. While there has been limited experience with HMDs during IMC, conflicting orientation cues and head-tracker performance appears to cause problems. Modern HUD designs incorporate features to mitigate SDO. More importantly, HUD flight testing now includes unusual attitude recovery. It is not clear what the results will be when HMDs are widely used during IMC operations. If conflicting references and head-tracker problems can be resolved, HMDs will be used in IMC operations, particularly in helicopters and tilt-rotor aircraft. Attention to SDO issues will have to be the same as is currently applied in HUD development.

BACKGROUND

Spatial disorientation (SDO) of pilots has been a persistent problem in aviation since the first flight into (and probable spiral dive out of) a cloud. Yet in the early 1980s, head-up displays (HUDs) were blamed as causing SDO. This bad reputation has persisted to the present. What prompted this criticism and is it warranted?

The HUD/SDO issue began with Barnette,⁽¹⁾ who surveyed Air Force pilots flying HUD-equipped airplanes and found that approximately thirty percent reported an increased tendency towards SDO. Newman later reported similar findings.⁽²⁾

HUD-induced SDO was reported to occur within one of several scenarios, the most common of which is flying in-and-out of clouds. Other SDO-sensitive situations include such extreme maneuvers as night pull-ups from a target, air combat maneuvering (ACM), and UA recoveries. With or without a HUD, these are conditions under which SDO tendencies are most likely to occur.

At the time these two studies were performed, the first HUDs had recently become operational. These early HUDs were intended as weapon aiming devices although limited flight data had been included in their symbology. It is important to remember this point: The HUDs were not developed as flight instruments nor were they tested as such.

In a later survey, Newman and Foxworth⁽³⁾ found a reduced tendency to SDO was reported by F-18 pilots and that no *Mercury* pilot reported an increased tendency to SDO.

Newman and Foxworth attributed the improvement in these results to better cockpit/HUD integration and better HUD training.

HUD Characteristics

HUD characteristics which create difficulty in interpreting orientation cues include:

- Poor Upright Versus Inverted Cues: Conventional attitude indicators (ADIs) use black (or brown) and blue (or light gray) hemispheres to denote earth and sky. These hemispheres help the pilot distinguish upright from inverted flight. Many ADIs also provide patterns on one or both hemispheres to simulate ground texture or clouds.

The HUD, on the other hand, is limited to monochromatic lines and must avoid textures and patterns which might block external visual cues. It is unlikely that HUDs will be able to incorporate color with sufficient contrast in the foreseeable future. Regardless of technological advances, it is not be practical to use blue and brown to denote sky and ground; blue symbols would not be clearly visible against the actual sky, and brown symbols would not sufficiently contrast with some terrain.

Such coding schemes by themselves, however, are unlikely to be entirely successful during the dynamic situation of a UA recovery.

- Clutter: A visually cluttered display can prevent the pilot from interpreting the cues needed for prompt recognition and recovery from UAs. The 2½° pitch line spacing on early F-16 HUDs has been criticized as distracting clutter, as has the presentation of excessive data on this and other HUDs. In an extreme UA, almost complete declutter may be necessary until the airplane has been stabilized.
- Digital Data and Rate Information: The HUD's digital displays have been criticized by some pilots because they make the determination of airspeed and altitude rate information difficult. This seems to be more of a problem with airspeed than altitude, since the velocity vector provides altitude rate information. Incorporating a flight path acceleration cue could assist the pilot in airspeed control.

Recent HUDs incorporate circular scales with a pointer and reference marks surrounding the digital airspeed and altitude displays.(4) When either airspeed or altitude change, the circular motion of the pointer provides the pilot with rate information.

- Full Scale Pitch Angles: It can be difficult to assess aircraft pitch attitude with the HUD's full scale but limited FOV display. The conventional ADI's compressed angular scales make aircraft attitude interpretation easier during dynamic maneuvering. The compressed scales slow down the angular rates on the display and the wider FOV keeps the displayed horizon in view.

Early HUD studies in the United Kingdom found that a slight pitch scale compression resulted in tighter approach tracking performance than did 1:1 scaling.(5) Later studies found that pitch scale compression could also be helpful during ACM or acrobatics.(6) Pitch scale compression is helpful during UA recognition and recovery as well.(7)

- Pitch Ladder Precession Passing Zenith or Nadir: Many early HUDs rolled their pitch ladders 180° when the airplane's velocity vector passes through 90° nose-up or nose-down. This was incorporated in their design to emulate the familiar controlled precession made by most ADIs to avoid gimbal lock. At best, this rotation in the HUD's reference frame makes controlled flight difficult during nose-up or -down attitudes; at worst, it creates disorientation. In an F-15 UA incident,(8) the negative effect of this HUD feature is apparent. The pilot stated that he rolled wings-level and pulled, when, in fact, viewing of the videotape frame-by-frame shows that he actually pulled through from the inverted position in a split-S recovery. The apparent roll was actually the display's controlled precession. Fortunately, this “feature” has been omitted from later HUDs.
- Accommodation Traps: The issue of HUD accommodation traps has been raised by Roscoe and his students, who maintain that the pilot's eyes will accommodate to a relatively close distance, in spite of the HUD symbology being collimated to optical infinity.(9-12) They assert, that when the pilot shifts focus between HUD symbols and real world objects, these large changes in accommodation produce SDO.

HUD studies have not supported this accommodation concern. Additionally, while the accommodation argument would predict HUD landing approaches which are much shallower and have greater dispersion than non-HUD approaches,(13) every HUD study to date has indicated the opposite.

In any event, the accommodation distance of the HUD would be at least as far as that of conventional instruments, and there have been no suggestions that looking from head-down instruments to the outside scene causes disorientation.

- Framing: Another concern is the sense of verticality imposed by the combiner structure or, in some HUDs, by the symbology itself.(14) During the F-15 incident described above,(8) the airplane was rolled 90° while the pilot thought he was wings-level. As observed on the videotape, the vertical altitude and airspeed scales, along with the heading scale, led to this sense of verticality. The edges of the pitch ladder, lining up in horizontal rows, emphasized this effect.

Conventional head-down ADIs are round, thereby avoiding part of this problem. Many ADIs also have pitch lines that lengthen as they extend further below the horizon and thus do not form parallel lines. This does not lead to a false sense of horizontal orientation when the airplane is rolled 90°.

- Velocity Vector Control -- γ versus θ : The tendency of pilots to use the HUD velocity vector as a control parameter can result in problems during UAs. Particularly at large angles-of-attack (α 's), this can create situations in which the pilot needs to push on the control stick, but pulls instead because of the extreme negative flight path angle(γ). This confusion results from pilots' standard training experience using aircraft pitch (θ) as a control parameter.

The Klopstein HUD symbology was the first design to emphasize the angular θ - γ - α relationship.(15) This format was not widely accepted because it used an early symbol generator which could only produce a set of straight lines and displayed no airspeed or altitude data. Its critics admitted however, that a pilot could use the α presentation well enough to allow for precise pitch and airspeed control. This format is shown in Figure 1.

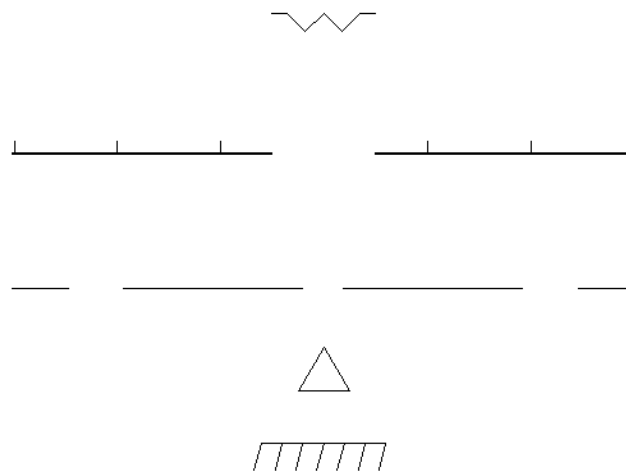


Figure 1: Klopstein HUD Symbology

HMD Characteristics

Helmet- (or head-mounted) displays, HMDs share many of these characteristics with their HUD cousins. In addition, there are two HMD-unique characteristics which appear to exacerbate spatial disorientation:

- Conflicting Frames of Reference: Newman (16) reported difficulty with the *Apache* hover symbology (a plan view with aircraft nose oriented up) superimposed on a direct view of sensor imagery. Such a combination of coordinate systems was difficult for pilots to interpret.

Because of the need to maintain spatial orientation, the HMD symbology will require some attention to incorporating cues to assist in the maintenance of orientation and in the detection and recovery from unusual attitudes. Newman (17) and Chandra (18) discuss symbologies for maintenance of spatial orientation.

- Head Tracker Shortcomings: Key concerns for any head tracker system (HTS) are the accuracy, the repeatability, and the latency of the measurements. Generally, the

accuracy of the pointing should be commensurate with the need for image registration. "Swimming" of the symbology because of HTS deficiencies has also been reported.

Latency is also a key issue. The head tracker must follow the pilot's head without excessive lag. No specific requirements have been determined, but the responses should be fast enough to minimize display image lag if head-tracked flight symbols or head-steered images are used. Based on the normal 4X measured rate for data latency (17), a preliminary figure of 20 msec (50 Hz) should be a first estimate. The head tracker responses should be of the order of 120-240 deg/sec.

There are normally four dynamic degrees of freedom for the pilots head, three angles, elevation; azimuth; and tilt; and one translation (leaning forward). Leaning forward is considered in many HUD designs which define an *alert eye position* (AEP) somewhat forward of the DEP. Lateral translation may be important if the cockpit geometry requires leaning to the side to see out.

Some head-tracking systems have ignored head-tilt. These systems have not usually presented symbology stabilized in either aircraft or world coordinates. As a result, there was little effect of head tilt. In most future systems, using aircraft or world stabilized symbology, ignoring head-tilt would lead to conflicts as the pilot looked through the head.

There have been anecdotal reports of difficulties with large pilots moving out of the head-motion box when the look down over the nose.

Novel HDD Designs

Many novel head-down display designs are departing from the traditional attitude ball or its cousins. Some of these displays have characteristics that may interfere with UA recognition and recovery.

- Pathway-in-the-Sky: The various pathway formats are described as intuitive, natural displays. None-the-less, they all contain a multitude of line segments which may conflict with a sense of attitude awareness. Few studies have been performed to assess any difficulties. These formats are very compelling and may overwhelm the background display of attitude information.
- Synthetic or Enhanced Vision: Many of these displays are poor quality pictures of the terrain. Photorealistic images seem to detract from the pilot's ability to detect ridge lines.(19) In mountainous terrain, the true horizontal may be hidden. The presentation of the view ahead of the aircraft in place of an attitude display must ensure that correct attitude information is conveyed. Few studies have been performed to assess any difficulties.
- Automatic Declutter: Some electronic attitude indicators remove "unneeded" information, such as mode annunciation, during extreme attitudes -- a process designed to

enhance the ability of the pilot to use the display for recovery without distraction. This removes mode awareness from the pilot and was thought to have contributed to the accident to the Airbus A-330 at Toulouse. The flight control mode had just switched to a mode which removed some pitch limits. This declutter may have contributed to the accident.*

DEVELOPMENT OF HUDS AND HUD STANDARDS

First Step -- F-18

The F-18 HUD was the first operational HUD intended for use as a flight display throughout flight and is shown in figure 2.. Prior to the F-18, HUDs were developed for specific flight tasks, usually weapon aiming or approach monitoring, and were not designed or tested for use in routine flight tasks.

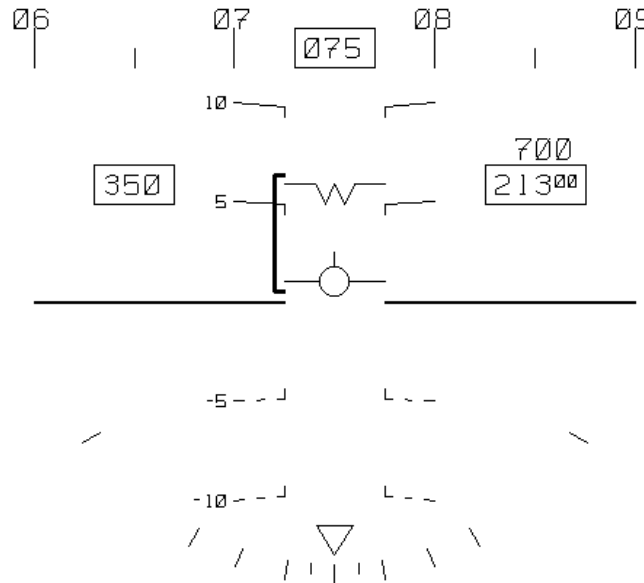


Figure 2: F-18 HUD Symbology

The F-18 HUD incorporated articulated pitch ladder lines (bendy bars). The pitch lines were inclined at half the pitch angle forming a series of V's pointing to the horizon. The V's became more compelling the further away from the horizon.

The F-18 also allowed the pilot to select a caged or uncaged flight path marker (FPM). The caged FPM was constrained to the center of the FOV. When the FPM was caged, a ghost marker was drawn to indicate where the airplane trajectory was going. The F-18 also used digital airspeed and altitude cues.

* H. B. Green (FAA, Seattle), personal communication, September 1994

RAE FastJet

In the 1980s, the Royal Aircraft Establishment (RAE, now DERA), at Bedford developed the FastJet HUD symbology for the *Harrier* and *Tornado* aircraft. The FastJet symbology is shown in figure 3. The goal of the FastJet format was to ease the pilot's task in routine and dynamic flight tasks. The major features are a tapered pitch ladder with variable scaling, a full-time caged climb-dive marker (CDM), pitch rate quickening for the CDM, and counter-pointer scales for airspeed and altitude.

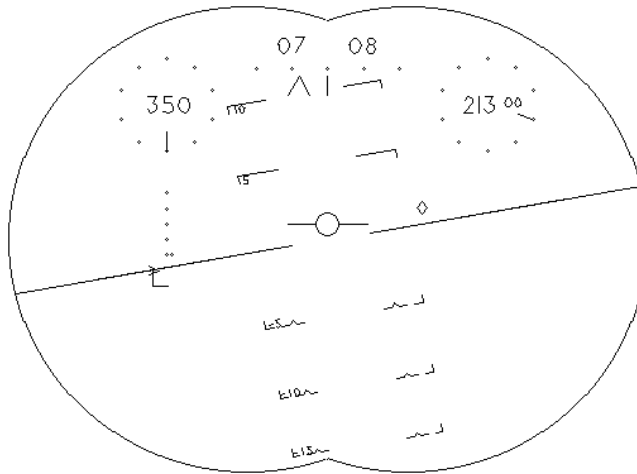


Figure 3: FastJet HUD Symbology

The pitch ladder* incorporated scaling which ranged from 1:1 when the CDM is within five degrees of the horizon and varied linearly to 4.4:1 at the zenith and nadir. The value of 4.4 was an accident of the FOV of the *Harrier* HUD.† Early on, a decision had been made to use 5° pitch spacing up to 30° and 10° spacing thereafter. A second, independent decision was made to set the scaling to ensure that three lines were present in the FOV at any time. These two decisions, when matched with the 15° FOV of the *Harrier* led to 2:1 scaling at an angle of 30°. This extrapolates to 4.4:1 at the zenith and nadir. The FastJet pitch ladder tapers as the angle from the horizon increases to give a sense of attitude awareness.

The FastJet flight symbol is a caged climb-dive marker with no option to uncage. A velocity vector symbol (a small diamond) shows the trajectory, but this is not intended to be an aircraft control symbol. No pitch marker is shown. Because of the elimination of the pitch reference, the CDM incorporates pitch rate quickening based on *Harrier* flight characteristics.

Finally, the airspeed and altitude scales are counter-pointers incorporating both circular dials and digital readouts.

* Purists may object to our use of pitch ladder claiming the correct term is “climb-dive ladder.” We continue to use pitch ladder for historical reasons and for economy of syllables.

† John Hall (RAE, now DERA, Bedford), personal communication, 1991

MIL-STD-1787

In the 1980s, the US Air Force inaugurated a program to develop a standardized HUD symbology. The result, shown in figure 4, was based on the RAE FastJet symbology with the addition of some navigation and guidance cues.

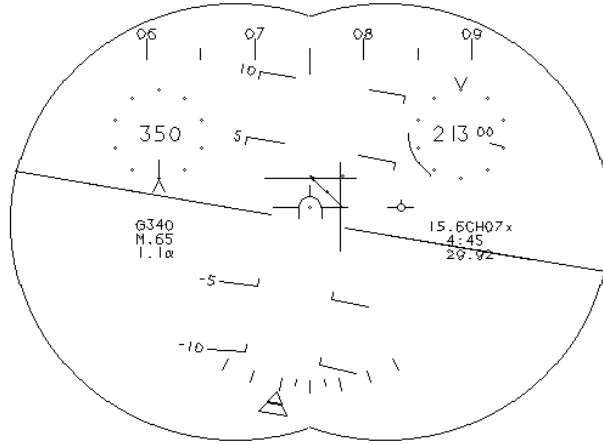


Figure 4: MIL-STD-1787 HUD Symbology

The pitch ladder was changed from tapered (in the FastJet) to an asymmetric format -- articulated below the horizon and tapered above. The CDM and FPM symbols were changed and an HSI-like symbol overlaid on the CDM for lateral deviation. A conventional glideslope indicator and split axis flight director cues were added. A number of digital readouts for acceleration, groundspeed, and vertical velocity were added.

Quickening of the CDM was retained, although the initial standard mandated the *Harrier* algorithm.

Civil HUD Development

In the 1980s, Flight Dynamics developed a HUD intended for flying category IIIa ILS approaches.(20) The symbology, shown in figure 5, was developed from the NASA HUD studies of the 1970s.(21)

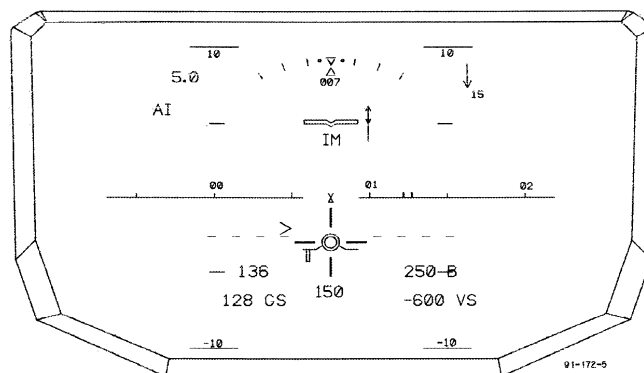


Figure 5: Flight Dynamics HUD Symbology

The pitch ladder is oriented around the pitch marker, not the FPM. The airspeed, altitude, and vertical speed cues are digital readouts arranged around the FPM. Heading is shown on the horizon.

The pitch ladder is quite understated when compared with military HUDs. (This HUD was intended for use only during ILS approaches, although there is no proscription against its use during other flight regimes.) The pitch scaling is 1:1 until the horizon would leave the FOV. As pitch is increased, the scaling is adjusted to retain the horizon line within the FOV.

Military Transport HUD Development

The C-130J HUD was developed using features from the FastJet, MIL-STD-1787, and Flight Dynamics symbologies. The pitch ladder was kept at 1:1 during normal operations with no tapering or articulation. (Neither would be discernible during C-130 operations). The original design followed F-18 caging/uncaging logic, primarily because of certification issues. Operationally, a caged FPM (otherwise known as a CDM) is intended. The pitch ladder rotated around the CDM or FPM as appropriate.

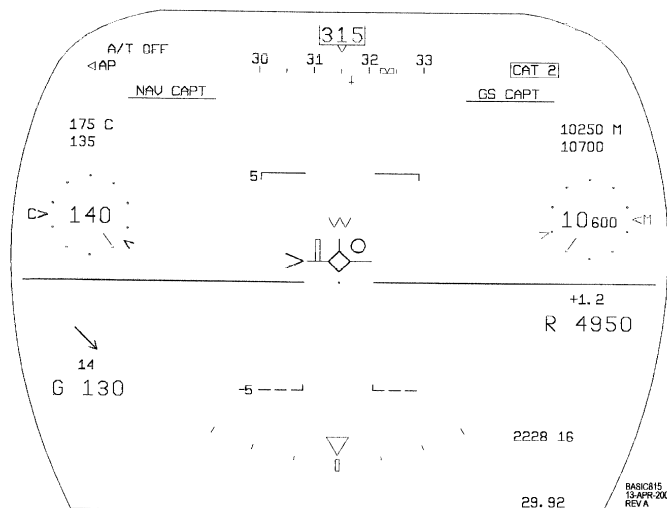


Figure 6: C-130J HUD Symbology

The HUD switches automatically to an unusual attitude mode when pitch or bank exceeds trigger values. The UA mode is pitch based with the pitch ladder rotating around the pitch marker. During nose-low UAs, an Augie Arrow is drawn. During nose high UAs, the Augie Arrow is omitted, but extra cues are added to the pitch ladder emphasizing the recovery.

Military HMD Standard

The only HMD standard that has been published is MIL-STD-1295 describing the AH-64, *Apache* system.⁽²²⁾ All symbologies are screen-fixed. Two symbologies, Hover

and Cruise, are shown in figures 7 and 8. The third mode, Transition, has a symbology similar to the Hover mode.

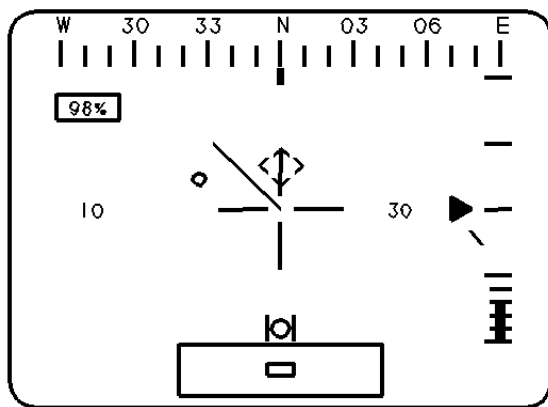


Figure 7: MIL-STD-1295A Hover Symbology

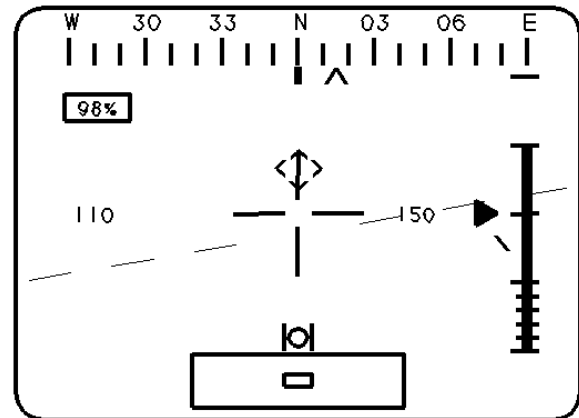


Figure 8: MIL-STD-1295A Cruise Symbology

This HMD appears to have been simply adapted from what would have been presented on a fixed HUD. Altitude is shown both digitally and with a thermometer scale. Vertical speed is shown as a moving caret. All altitude information is on the left. Airspeed is shown digitally on the left.

Aircraft heading is shown as a conventional tape and lubber line at the top of the display. Sideslip information is shown in a ball-bank format at the bottom of the display

The hover symbology is a screen-fixed plan view (God's eye view) of the scene. The hover velocity vector (hereafter called the hover vector) is shown emanating from a reticle. There is also an aiding cue (a small circle) showing acceleration. The scaling of the hover vector is full length equals six knots groundspeed.

The transition symbology is similar to the hover symbology, except for scaling of the hover vector and the addition of the screen-fixed horizon line. The scaling of the hover vector is full length equals sixty knots groundspeed (i. e., ten times the hover symbology).

UNUSUAL ATTITUDE RECOVERY RESEARCH

HUD Studies

A comparison of HUD-based and ADI-based unusual attitude recoveries from unusual attitudes (UAs) was studied by Kinsley, Warner, and Gleisner.⁽²³⁾ Both a static format and a fixed-base simulation of F-18 airframe aircraft dynamics were used for the evaluations. Their results show that use of the ADI ball resulted in faster reaction times

and faster overall recovery times than with the HUD format. They found that the visual background interacted with recoveries using the HUD.

In 1986, Guttman compared the F-18 HUD with an electronic ADI (EADI) during UAs in a fixed-base generic simulator.(24) The results showed that an EADI produces superior recoveries than does a HUD.

Recovery from unusual attitudes was studied by Newman in a study using an F-14 simulator at Patuxent River.(7, 25)* Several variations on a modified F-18 HUD symbology were studied separately. Several modifications were recommended to enhance spatial awareness or to ease of recovery from unusual attitudes: (1) Pitch scale compression (2) Automatic change from 1:1 to compressed pitch during unusual attitudes; (3) Adding an arrow (Augie arrow) to indicate the recovery direction; and (4) F-18-style slanted pitch lines. No benefit of asymmetric pitch ladder design was found.

Deaton and co-workers examined the effect of various HUD pitch ladders on unusual attitude recovery and on the ability of the pilot to detect outside visual targets.(26) They concluded that an enhanced pitch ladder with slanted pitch lines and "sharks teeth" at extreme nose-low angles.

Deaton and associates also examined the effect of orientation cues imbedded in the HUD symbology. They found the Augie arrow developed earlier(7) to be effective in aiding the pilot during recoveries from unusual attitudes.(27) Chandra and Weintraub found similar results.(18, 28)

In 1989, the Air Force School of Aerospace Medicine (now Armstrong Laboratory) reported the results of static evaluations of various pitch ladder formats on orientation recognition.(29) Ercoline *et al.* compared articulated (i. e. slanted) pitch ladder lines and combined lines (with articulated lines below the and straight lines above). The combined format was presented in three versions: all lines of equal length; lines becoming shorter (tapering) as the angle from the horizon increases; and lines becoming thicker at extreme negative pitch angles.

The results for pitch recognition favored articulated pitch lines and increasing the thickness as the angle increases from the horizon. For bank orientation, the conclusion was drawn that lateral asymmetry favored bank recognition.

Later studies, however, concluded that articulated pitch ladder lines created problems with bank recognition during unusual attitudes. In 1990, the UK studied alternative pitch ladder formats for the multi-national European Fighter Aircraft (EFA). The EFA HUD was to have used F-18 style pitch ladders. The UK Ministry of Defence evaluated this pitch ladder with the tapered pitch lines of the Fast-Jet. The simulation was conducted on the RAE's simulator which has large amplitude motion cues and a g-seat.

* Although this study was conducted at Patuxent River NAS, it was sponsored by the Flight Dynamics Laboratory at Wright-Patterson AFB.

The results show a clear subjective and objective preference for tapered pitch ladders over the articulated pitch ladders.(30) Several pilots made 180° errors in judging bank with the articulated lines and rolled the wrong way during recoveries. This observation was supported by a USAF-sponsored study by Weinstein and Ercoline (31) who noted that a large number of evaluation pilots were unable to discern inverted flight and attempted split-S recoveries thus increasing the dive angle.

Ercoline and Gillingham also evaluated airspeed and altitude scales, comparing conventional tapes with various and digital plus cue formats. The task was maintenance of airspeed and altitude in the presence of disturbances. The results are being evaluated at present. Results indicate that digits plus counter-pointers are preferred. Vertical tapes tended to promote a large number of incorrect responses.(32)

Current FAA certification practice include evaluation of unusual attitude recoveries during flight tests. Normally, the most cluttered navigation format is used during UA recoveries. Automatic declutter of navigation data has been incorporated in some HUDs to avoid a cluttered format.(33)

HMD Studies

Fixed-wing: Osgood, Geiselman, and Calhoun (34) and Geiselman and Osgood (35-37) developed a symbology (The Theta format) to aid in unusual attitude encounters. Osgood *et al.*(34) compared using a HUD with a combination of HUD/HMD for attitude control and concluded that the combination of HUD and HMD was superior. Geiselman and Osgood (37) studied several fixed-wing symbologies designed to convey aircraft orientation while the pilot was looking off-axis. They determined that ownship information enhanced the ability of the pilot to spend more time looking off-axis (and presumably looking for targets).

DeVilbiss, Ercoline, and Sipes.(38) addressed the effect of off-axis targeting and unusual attitude recovery. In their experiment, the pilot was required to acquire a target and then recover from a UA. They found that when pilots were looking off-axis with no flight instrumentation in their view, recoveries from UAs were delayed by about 1/2 second -- the time necessary to look at the HUD to begin recovery. They found that, by displaying HUD (screen-fixed) information on the HMD, recoveries could begin sooner. This study did not evaluate the usefulness of screen-fixed symbology on mission performance, only on UA recovery.

Jones *et al.*(39) had pilots fly simulated air-to-air missions. There were more attitude judgment errors with conformal* symbology. There was no statistical difference in subjective opinion data and none in judging target aircraft relative attitude.

Recently, Cacioppo and co-workers examined the optokinetic-cervical reflex (OKCR) and its relation to head position and attitude interpretation in fixed-wing pilots.(40-42)

* In their terminology, conformal means world-fixed.

The OKCR causes pilots to tilt their heads in an apparent attempt to align their eyes with the horizon. These studies indicate that pilots maintain orientation with the aircraft reference during IMC flight, but tend to tilt their heads to the real-world during VMC flight. The observation was made that the OKCR could be an effector of SDO, particularly during IMC/VMC transition. The studies were carried out in simulators (40-41), but the effect has been observed in flight (42).

Merryman and Cacioppo (42) conclude that this effect could be conducive to SDO as a pilot moves his head during flight and that this effect must be taken into account during the design of head-mounted attitude flight displays.

Rotary-wing: Haworth and Seery (43) examined several improvements on AH-64, *Apache* symbols. Their test results indicate that pilots perform significantly better when using world fixed symbology over the standard *Apache* screen-fixed symbol set. Haworth and Seery did note that both the standard and modified symbology caused incorrect cyclic inputs during hover tasks while looking off-axis. They recommended further improvements in hover symbology

Haworth *et al.* (44) studied the effect of different stabilizations based on AH-64, *Apache* symbols. The performance improved with world-fixed FPM and horizon combined with screen-fixed non-spatial data (airspeed, etc.) Best symbols set appeared to be *Long-bow Apache* plus uncompressed pitch ladder, compass rose, and ownship symbol with horizon world-fixed and visible off-axis.

Other Studies

Non-traditional symbologies, such as pathway-in-the-sky (PITS) are being developed. In addition, the use of both sensor images and database terrain are being considered. What effect will these have on spatial awareness and unusual attitude recovery?

Reising, Barthelemy, and Hartsock (45) compared unusual attitude recoveries using two HUD formats and a pathway format. In this experiment, the PITS display commanded the recovery in accordance with standard USAF procedures. Nevertheless, the average reaction times were significantly slower (about 100 msec) with the PITS than with either HUD. Following the main experiment, the pilots were given five days of practice with the PITS and were able to recover slightly faster than with the HUDs. Their conclusion was that the PITS was potentially better than the conventional display. To this reader, this conclusion doesn't seem to fit.

Braithewaite, Durnford, and Wildzunas (46) developed a novel flight display (shown in figure 9) which they tested in a UH-60 simulator. Both objective and subjective results indicate improved spatial awareness. In particular, the time to achieve wings-level flight was significantly faster.

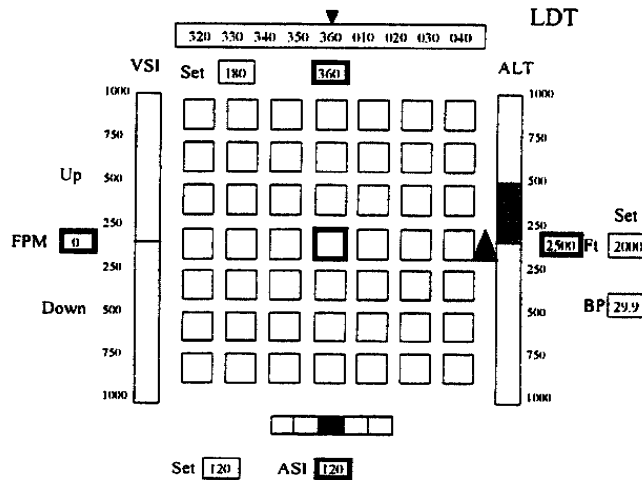


Figure 9: Novel Display in Left Descending Turn, Braithewaite *et al.* (46)

UNUSUAL ATTITUDE RECOVERY TECHNIQUES

An overall reassessment of UA recovery techniques is essential at this point in time, particularly with HUD-equipped airplanes. In a critical UA, the airplane is likely to be in an extreme nose-high or nose-low attitude and body axis rates may be quite high. Immediate recovery is imperative.

Fortunately, the typical UA is not critical. Most UAs are noticed when the airplane has just begun to depart from level, unaccelerated flight. Recovery from these UAs can be accomplished using normal instrument techniques. Most instrument flight manuals direct their UA recovery techniques to these mild excursions.

A critical UA, however, exceeds these standard handbook recovery techniques. Recovery must be rapid and instinctively clear to the pilot who may be confused, disoriented, and possibly incapacitated by g forces.

Review of HUD Characteristics

A basic issue of HUD symbology design has been whether its primary objective should be to keep the pilot oriented or to facilitate recovery from a UA. Although, clearly, maintenance of orientation is a priority, pilots will occasionally enter extreme UAs regardless of the symbology and rapid recovery is then paramount. A slightly non-optimum symbology in terms of orientation maintenance, is a small price to pay for increased reaction time during a critical UA.

With electronic displays, such as the HUD, particularly with 1:1 or near 1:1 pitch scaling, the lines and symbols may be moving too fast for a pilot to assess aircraft attitude easily. In the midst of a UA, the pilot should not have to decide whether the aircraft is nose-high or nose-low, upright or inverted -- the display in use should clearly indicate the recovery.

Judicious declutter of data not needed for recovery should be considered. However, important information, such as mode annunciation, should remain available. (This may be an argument against excessive mode annunciations on the primary flight display.)

Before reviewing the recovery techniques, we should review features of electronic displays that influence recoveries. Table I summarizes those features of HUDs applicable to UA recognition and recovery.

Table I: Unusual Attitude Features of HUD Standards

Format	UA Mode	Pitch Ladder	Scaling	Pivot	Aircraft Symbol	Other Cue	Scales
F-18	No	"bendy bars"	1:1	Pitch Marker	CDM or FPM	-	Digital
FastJet	No	tapered	variable	CDM	CDM	-	CP's
MS-1787	No	tapered/bendy	1:1	CDM	CDM	ghost horizon	CP's
B-727	No	straight	variable	Pitch Marker	FPM	-	Digital
C-130J	Yes	straight	1:1	Pitch Marker	Pitch Marker	Augie arrow	CP's

Tactical Aircraft Recoveries

The UA recovery technique, normally practiced with the old-style artificial horizons, should be relied on as the basis for UA recoveries with all monochrome electronic displays (HUDs and HMDs). This technique called on the pilot to roll to the horizon, and did not require a decision about whether the airplane was upright or inverted.

Adapting this UA recovery for a HUD-equipped airplane, the pilot would roll the wings-level, positioning the horizon above him, then pull the nose to the horizon.

With a compressed pitch ladder, tapering or an Augie Arrow should provide adequate information for this recovery. During a UA, the pilot need only roll toward the arrow and then pull to the horizon. While the pitch ladder may be moving too fast to read during the roll, once the airplane is wings-level, its motion should be slow enough for the pilot to assess his attitude and assist his pull to the horizon. With bendy-bars, the pitch ladder should support this cue, although the rapid display motion probably prevents full use of this cue.

In the more critical, nose-low situation, the effect of this recovery will be to roll upright and then pull to the horizon.

In the nose-high situation, the initial roll will lead into an inverted, nose-high position and a subsequent pull down to the horizon, leaving the aircraft in an inverted. Such a stabilized inverted attitude is not considered to be a problem in a tactical or trainer aircraft.

Transport Recoveries

From a recognition viewpoint, tapering, bendy-bars, or compression are probably not of much help for the typical attitudes flown by transport aircraft.

The previous UA recovery technique described above, may not be suitable for transports or helicopters. Alternative techniques which do not lead to inverted recoveries from nose-high UAs, should be considered for transports. Appropriate recovery techniques will depend on the pilot recognizing the difference between a nose-high and a nose-low UA. Obviously, interpretation of the display to make this nose-high/nose-low determination will slightly delay the start of the recovery. For a transport, the HUD should display the Augie Arrow only for nose-low UAs as is the case for the C-130J.

One of two nose-high recovery techniques should be followed, probably dependent on the type of aircraft. Either a roll to a near-90° bank with a slice-back to a near-level pitch attitude, followed by recovery to a wings-level upright position or roll to a wings-level, nose-high, upright attitude, then ease back to a level pitch attitude.

The nose-low recovery technique should be the same for transports as for tactical aircraft: the pilot rolls upright and pulls to the horizon.

CONCLUSIONS AND RECOMMENDATIONS

HUDs: Head-up displays (HUDs) do not cause spatial disorientation. They do have some features which can be improved to provide pilots with more help during UA recoveries. Overall, the advantages of HUDs far outweigh any disadvantages.

The research into HUD spatial awareness produced several benefits: symbology modification, UA recovery standardization and pilot training, and incorporation of UA recoveries into test and evaluation.

HMDs: Unfortunately, we can't say the same about HMDs at this time. The current level of HMD spatial orientation is about where HUDs were in the mid 1980's. More work is clearly needed:

- Does the HMD promote SDO? There is some evidence that conflicting orientation cues and head-tracker characteristics may contribute to the onset of SDO.
- Do we have a clear understanding of the best techniques to use to recover from an UA using a HUD?
- What symbology should be used in HMDs?

Novel HDDs: The situation is better with the novel displays (such as the pathway or synthetic vision), but SD and UA issues must be addressed. We must exercise the same care that we have with recent HUDs.

The NASA synthetic vision program is currently investigating general aviation applications with a heavy emphasis on the inadvertent IMC type of loss-of-control. Simulator experiments should begin in the very near future.

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ABBREVIATIONS

ACM	Air Combat Maneuver
ADI	Attitude (Director) Indicator
AH-64	Attack Helicopter, Boeing (nee McDonnell-Douglas, nee Hughes) <i>Apache</i>
C-130	Military Transport, Lockheed <i>Hercules</i>
CDM	Climb-Dive Marker
DERA	Defence Evaluation and Research Agency
F-15	Military Fighter, Boeing (nee McDonnell-Douglas) <i>Eagle</i>
F-16	Military Fighter, Lockheed (nee General Dynamics) <i>Fighting Falcon</i>
F-18	Military Fighter, Boeing (nee McDonnell-Douglas) <i>Hornet</i>
FOV	Field of View
FPM	Flight Path Marker
HMD	Head-or Helmet-Mounted Display
HUD	Head-Up Display
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
OKCR	Optokinetic-Cervical Reflex
PITS	Pathway-in-the-Sky
RAE	Royal Aircraft Establishment
SDO	Spatial Disorientation
UA	Unusual Attitude
UH-60	Military Helicopter, Sikorsky <i>Blackhawk</i>
VMC	Visual Meteorological Conditions

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